AD-A250 357

R&D 6509-PH-03
DAJA45-90-M-0265

2

Round Table Workshop on the Frontiers of Condensed Matter Physics

Broomcroft Hall, Manchester
24-25 September 1990

DTIC
SELECTE
MAY 19 1992
S B D

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

Report prepared by Allan I Solomon

92-13328

92 5 18 145

Contents

Introduction — Allan Solomon

Reviews

Quantum Optics — Roy Pike

Disordered and Frustrated Systems — David Sherrington

Magnetism and Magnetic Materials — Brian Rainford

Condensed Matter Physics — Raymond Bishop

Superconductivity - an overview — Colin Gough

Algebraic and Group Theoretical Methods — Mario Rasetti

Appendices on Funding

I. A Note on the Funding of "Mainstream" Physics in the UK — Brian Rainford

II. A Perspective on the Budget of the US Army Research Office — Mikael Ciftan

Annex to Appendix II

Accession For
NTIS GRA&I ☑
DTIC TAB ☐
Unannounced ☐
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or Special
A-1

Introduction

The impetus for holding a workshop on *The Frontiers of Condensed Matter Research,* had its genesis in an idea of Dr Mikael Ciftan, of the United States Army Research Office. Mike who is based in the US Army's Research Command in North Carolina, approached his onetime supervisor, Professor Larry Biedenharn, with a view to finding out what was exercising Condensed Matter Physicists in Europe, with the emphasis on the the United Kingdom. Larry, with whom I serve on an international Theoretical Physics Committee, in turn contacted me. As I had had some experience of setting up conferences in the past, although usually of a more conventional nature, I accepted - especially as Dr Alan McKane, a fellow committee-member on the UK Institute of Physics Mathematical Physics Committee, agreed to help with the organization.

Thanks to Alan's connection with the University of Manchester, we were able to acquire the idyllic site of Broomcroft Hall, a residence used by senior visitors to the University.

The basic idea was to isolate six leading researchers over a 24-hour period, during which they would make presentations on a variety of topics in Condensed Matter Physics. Although by no means exhaustive - and it was not intended that they should be - the topics did include some of the most interesting questions in the area being attacked today, such as high-temperature superconductivity and unusual quantum states (squeezed states) of light, from the viewpoint of theoretician and experimenter, as well as indicating applications.

A common, but not universal, brief was to proceed from a discussion of the earlier background to the current status of the work, and thence to a glimpse at possible future trends.

I am very grateful to the participants for providing the material for this brief report and indeed for participating at short notice, and to Alan McKane for assistance with the organisation, as well as Dr Mikael Ciftan and Dr John Zavada for the concept and financial support from the US Army. Finally, my thanks to my secretary, Ann Melling, for help with the administration, and production of the report.

Allan Solomon
Open University
December 1990

Quantum Optics

E R Pike,
RSRE, Malvern and King's College, London

1. *Introduction and Background*

Quantum optics, although arguably dating from the invention of the laser some thirty years ago, is still a fast moving and fashionable area of physics research. This is exemplified by an increasing number of meetings and conferences; for example, the first NATO ARW on squeezed states of light was held in Cortina, Italy in January 1988, preceded by a special workshop funded by the London office of the US Office of Naval Research. A second NATO ARW will be held in the same location in January 1991. The proceedings of the ONR special workshop and the first ARW have been published *(Photons and Quantum Fluctuations,* eds E R Pike and H Walther, Adam Hilger, Bristol, 1988, *Squeezed and Non-classical Light,* eds E R Pike and P Tombesi, NATO ASI Series B, Vol 190, Plenum Press 1990) and the proceedings of the second ARW will also be published by Plenum Press. A new UK Institute of Physics Journal with this title was launched in mid 1989; its aim in broad terms is to cover theory and applications of optics where the quantum nature of the phenomena are of particular interest or importance. We analyse contributions to this journal below.

Much of the work involves non-linear interactions of radiation and matter and there is a substantial overlap with the equally popular modern topics of nonlinear dynamics and chaos. Indeed, the opportunities in quantum optics for realising non-linear phenomena for analysis are particularly abundant. For experimental work, time scales are much more convenient than, for example, in hydrodynamics where much of the earlier work on non-linear phenomena has been done. Useful early references across these two disciplines are *Quantum Chaos,* eds E R Pike and Sarben Sarkar, NATO ASI Series B, Vol lBl, Plenum Press, 1988, (proceedings of a NATO ARW held in Como, Italy in 1987) and *Frontiers in Quantum Optics* eds E R Pike and Sarben Sarkar, Adam Hilger, Bristol, 1986, (proceedings of a special "Malvern Symposium" funded by the UK MoD and run by RSRE Malvern in 1985). Earlier publications are the proceedings of two NATO ASI's: *Photon Correlation and Light-Beating Spectroscopy,* NATO ASI Series B, Vol 3 Plenum Press, 1974 and *Photon Correlation Spectroscopy and Velocimetry,* NATO ASI Series B, Vol 23 Plenum Press, 1977, both edited by E R Pike and H Z Cummins.

Although we will not cover the topic in this review, since it is only just emerging, we mention recent advances in the study of spatial nonlinearities and chaos in quantum optics which may be of great practical importance for the development of optical memory devices.

2. *Classifications in Current Modern Optics*

We may classify modern optics into four subdivisions, namely, classical optics, semi-classical optics, quantum electrodynamics and quantum optics. Classical optics is described by Maxwell's equations, which contain no quantum fluctuations. An example is diffraction theory. Semi-classical optics allows weak quantum fluctuations and describes, for example, optical bistability and optical chaos. Although long established, semi-classical optics can be considered as a sub-branch of quantum optics for convenience; it is particularly applicable when light fields are so intense that it is only necessary to quantise the electron system with which the radiation is interacting. Quantum electrodynamics describes simple relativistic electron-photon systems at zero temperature. Examples are the calculation of the Lamb shift of levels of the hydrogen atom or the gyromagnetic ratio of the proton. Finally quantum optics covers non-relativistic, non-trivial, electron-photon systems with finite-temperature heat baths. In this case there are not only fluctuations arising from the quantised vacuum and photon field, but also additional fluctuations from the dissipative interactions with the heat bath.

Particularly relevent to current research are "squeezed" states of light which have fluctuations in either amplitude or in one quadrature of phase which are below the noise levels predicted by a simple application of the uncertainty principle. Since essentially all applications of optical beams are limited ultimately by this quantum (photon) noise, there are hopes of technological uses of such light beams for improved performance of a number of types of optical system. Some first experiments have already shown that improvements can be achieved in the measurement of absorption coefficients, in optical radar and in high-resolution interferometry.

3. *Present Theoretical Techniques and Problems*

3.1 *The Master Equation*

In a formal presentation of the subject one would start with a derivation of the equation for the density operator of an arbitrary electron-photon system immersed in a heat bath at finite temperature. This is the so-called master equation and it forms the basis for much of the work in the field. Its derivation is not straightforward and the approximations used are not very easily quantifiable, however, it seems to be adequate to describe many physical phenomena. We write it below

$$\frac{\partial \rho_S^{(I)}(t)}{\partial t} = -\frac{1}{\hbar^2}\int_0^t dt' \, Tr_B\Big[H_{SB}(t),\Big[H_{SB}(t'),\rho_S^{(I)}(t)\rho_B(0)\Big]\Big].$$

S denotes the system and B denotes the heat bath, $\rho_S^{(I)}$ is the density matrix of the system in the interaction representation and H_{SB} is the hamiltonian of the system plus bath. A derivation of this master equation can be found, for example, in *Radiation and Noise in Quantum Electronics, W H Louisell*, McGraw Hill, 1964.

3.2 *Semiclassical theory*

Starting from this master equation a semiclassical approximation can be made, in a way familiar to theoretical physicists who work with Green's function equations, by decoupling higher-order correlations between system and bath variables. Terms which arise such as $<a_k, J_{k'}^3>$ where a_k is an annihilation operator of the radiation field and $J_{k'}^3$ is a spin operator of an electron wave function, can be approximated by the product $<a_k><J_{k'}^3>$. A system of three coupled equations for the electric field, atomic polarisation and atomic inversion results. These are similar but not exactly equivalent to the traditional Maxwell-Bloch equations which are derived by a self-consistent approach to the propagation of a classical radiation field in a medium of quantised two-level atoms. The subject is as yet too young to comment on the subtle differences in the predictions of these two approaches.

The semiclassical approach has been enormously influential since it gives satisfactory treatments of phenomena such as laser theory and optical bistability where fluctuations are small. Optical bistability theory, in effect, is an extension of the theory of the laser to the case where an additional external field is injected into the laser cavity. One finds, in both cases, a satisfactory understanding of such experimental results as are available. For example, the thresholds of operation for lasing and for instability, respectively, and phase and amplitude noise values can be calculated. The importance of the phenomenon of optical bistability is related to the potential application of solid-state optically bistable devices in optical computing. A number of laboratories, using such devices in GaAs, InP or so called SEED in hybrid technology, have already demonstrated optical logic on a small scale. Unfortunately the promise of optical computing has been oversold prematurely in some quarters but, nevertheless, steady progress is being made and practical applications may yet emerge.

The semiclassical theory of coupled radiation-matter fields can be reduced to the famous Lorenz equations which have chaotic solutions for certain parameter regimes. A number of experiments have been published, particularly by the group of Arecchi in Florence, using far-infrared and CO_2 lasers which demonstrate such effects.

3.3 *Fokker-Planck Equation*

A different approximation scheme is required to include stronger quantum fluctuations and this may be attempted by a system-size expansion leading to a Fokker-Planck equation for the so-called Glauber P-representation of the radiation field. This representation, although fully quantum mechanical, has the advantage of the appearance of a classical probability function and has been widely used since its introduction by R Glauber in 1963. If the diffusive term in this Fokker-Planck equation is positive-definite then we may transform it into a set of Ito-Langevin stochastic differential equations which describe phenomena essentially classically but with added noise terms. This approach is sometimes called the "positive-P" method and has had a somewhat controvertial recent history. It is now realised that it is of somewhat limited application.

Attempts to salvage such an approach have been made which use the Wigner quasi-probability function in place of the Glauber P-function. This certainly has a wider applicability but the situation is still fluid and no generally applicable method is

available.

The Fokker–Planck equation, however, does give a more complete theory in some special cases than is obtained using the original semi-classical approach. An example is the theory of the laser near threshold .

3.4 *Non–classical Light*

The more recent developments in which squeezed states of light are studied require further refinement of the theory since the diffusive term in the Fokker–Planck equation is then not positive definite. The light field is then said to be non–classical and may be squeezed in either amplitude (photon number fluctuations smaller than the coherent–state limit) or in one quadrature of phase (phase fluctuations smaller than the coherent–state limit). Again no general methods are available but each situation has to be treated with suitable relevent approximations. Significant contributions have been made by the group of Walls in New Zealand and by the group of Giacobino in France.

Very small systems (up to fifty atoms) have been treated essentially exactly by sophisticated numerical techniques on a Cray computer by Sarkar and Satchell at RSRE, Malvern.

A popular example in which non–classical light is generated is that of parametric down–conversion. In this process a non–linear crystal is pumped by, say, an ultraviolet pump and the correlated signal and idler beams which emerge are in the long–wavelength region of the visible spectrum. The correlations between photon detections in the two output beams are used for the realisation of novel optical experiments.

A number of realisations of both amplitude and phase–squeezed light have now been reported. For example, in a degenerate parametric down–conversion experiment, amplitude squeezing of the order of 80% may now be acheived (Giacobino *et al.* Ecole Normale Superieure, unpublished).

One of the areas being investigated is the use of non–classical light beams in "quantum cryptography" where new ideas in covert communications are arising. Other topics to have been studied are new methods in optical radar using individual photons and "quantum non–demolition" experiments aimed at the basic understanding of the theory of measurement itself. In solid–state physics *per se* recent theoretical work by Artoni and Birman at CCNY has shown that polaritons are also examples of squeezed excitations.

4. *International comparisons*

A very rough estimate of comparitive activity in the field can be obtained by analysing the contributions to the IOPP Jounal *Quantum Optics*. This is an international journal by the provenance of its editorial board, which comprises some thirty leading scientists from many different countries. For workers in the field it is useful to have such a concentration of papers in one publication and for newcomers a good cross spectrum of activity can be found by perusing a few issues. The breakdown of published contributions since 1989 by country is as follows:

Country	Percentage
USA	15
UK	9
China	7
Austria	7
W Germany	5
USSR	5
Italy	5
Australasia	4
France	4
13 others	39

This table, although not particularly significant from a statistical point of view, does reflect the very widespread interest around the world in the subject and promises for rapid progress in the future. The weight of research in the UK may be over represented, since the journal is published there, but the Science and Engineering Research Council has launched a special initiative for funding research in this field and the UK contribution is not insignificant. The following sketch list will give some idea of the magnitude and scope of current UK work in this field.

Institution	Name(s)	Topic
British Telecom	O'Mahoney	Amplification
Univ of Essex	Loudon	Squeezing, amplifiers
Herriot Watt	Harrison, Moloney	Bistability, chaos, SBS
King's College	Pike, Sarkar, Barnett	Polaritons, chaos, QED
Univ of Manchester	Bullough	Rydberg atoms
Imperial College	Knight	Squeezing, Rydberg atoms
Open University	Solomon	Exotic states
RSRE	Rarity, Tapster	Downconversion, amp squeezing
Univ of Southampton	Hanna	Fibre lasers

Moloney at Herriot Watt has a strong position in spatial non-linearities, having performed some of the earliest experiments in this area. Solomon brings a welcome algebraic mathematical expertise into the subject and Hanna's group in Southampton have been world leaders for a number of years in the development and application of special optical fibres. Knight at Imperial is the coordinator of the SERC's special initiative and has a broad knowledge of the UK and international scene. Loudon at Essex, formerly also of RSRE, is a renowned theorist and has written one of the standard textbooks: *Quantum Theory of Light* for Oxford University Press.

Not evident from this table is the close connection between the two groups at RSRE, Malvern and at King's College, London, where the author of this report has joint appointments. Dr Sarkar has only recently transferred from RSRE to King's College; together we have recently completed the manuscript of a new book *Quantum Theory of Radiation* also for the Oxford University Press. These two groups have particular strengths, for example in the field of amplitude squeezing and its applications, which is based on a long history of work in photon statistics and optical applications at RSRE.

This work, in fact, gave rise to new field called "photon correlation spectroscopy" and an instrument for the analysis of the fluctuations, both statistical and spectral, of optical radiation sources known as the Malvern Correlator or Photon Correlator. Such instruments are now manufactured by some half-dozen companies in different countries of the world and can be found in many University and Industrial research laboratories where the technique is used for a variety of applications. The two most important of these perhaps are, firstly, in submicron particle sizing, of for example proteins, viruses, enzymes and polymers, where laser scattering from Brownian motion using photon correlation spectroscopy has been a standard technique for many years and, secondly, in high-speed laser Doppler spectroscopy, where photon correlation has been used extensively, for example, for supersonic wind-tunnel studies and for the analysis and improvement of the performance of aero-engines, internal combustion engines and turbochargers.

It can thus be seen that quantum optics has been paying its way for quite a long while now, in the sense of providing profitable uses for the measurement of photon fluctuations, using the ordinary laser as a source, and we are hopeful of other practical applications being found which make use of the newer squeezed sources which are being developed at the present time.

5. *Conclusions*

Although there are a number of fundamental areas of quantum optics which deal with the interaction of light with free atomic or molecular beams or trapped single atoms or molecules, there are also other areas which have close connections with condensed matter physics which have been and will continue to be of acute importance for future technological applications. In particular we single out potential developments in optical storage and optical computing and also information transmission. It is much too early to say, however, where the next significant payoff will arise and what its value will be. We might compare the state of the art for squeezed light at present to that immediately after the invention of the laser itself when the future areas of application could hardly have been dreamed about. The next few years will surely provide some of the answers.

Disordered and Frustrated Systems in Condensed Matter Physics and Conceptual Applications in Hard Optimization and Neural Networks

David Sherrington
Dept. of Physics , University of Oxford

The last decade and a half has seen great changes in the realization of the relevance of quenched disorder and competing interactions or rules in condensed matter physics and more broadly in systems with many interacting units. Indeed, there has occurred a revolution in thinking, in which these features have been transformed from being a "nuisance to be approximated away" to realizing that they provide a whole new world of interesting phenomena with a plethora of opportunities for utilization.

Concerning disorder alone, one has seen the phenomenon of localization, both strong and weak, in electronic, optical, phononic and magnetic systems, with consequences for example in conductivity (metal-insulator transitions, universal conductance fluctuations), the quantized Hall effect and in enhanced back-scattering (e.g. white paint). Amorphous structures, semiconducting, metallic or insulating, offer new conceptual challenges and technical possibilities (e.g. amorphous magnetic metallic alloy ribbons in transformers). Porous media are ubiquitous in nature and the properties of fluids therein are not only of scientific interest (since many of the usual prejudices of period systems are inappropriate, e.g. for wetting, for flow, for conductivity and dielectric response) but also of great practical relevance (e.g. to the petro-chemical and food industries, as well as in the interpretation of signals passing through the earth; indeed signal propagation through various disordered media is of great relevance in communications and analysis of distant objects)

Frustration alone is also of significant interest. This is typified by systems with competing forces, for example in solids in which there are different mechanisms favouring incompatible periodicities, either of atomic positions or of magnetic order (ANNNI models in magnetism, polytypism in material science). It can result in a single system having a plethora of different phases as some control parameter (e.g. temperature) is varied. It can also result in great dependence on interaction character (e.g. a simple Ising model on a triangular lattice has a phase transition if the interactions are ferromagnetic but not if they are antiferromagnetic).

The simultaneous combination of quenched disorder and frustration leads to an even larger set of new phenomena. One group of systems is the spin glasses, magnetic alloys with randomly mixed ferromagnetic and antiferromagnetic interactions. These exhibit an extremely rich thermodynamic structure, with a plethora of non-equivalent

thermodynamic states which have frozen magnetic moments but without periodic order, with hierarchical inter-relations and a chaotic-like dependence on global parameter changes. Associated with this are slow relaxation and remanence. Their understanding has required the development of new mathematical and computer-simulational techniques and the development of new concepts and modes of thought. Conceptually, spin glasses are much wider in their application, since the key ingredients of competing interactions and disorder are legion. Other examples in condensed matter physics include random antiferromagnets in a field and charge density waves in alloys. As important, or perhaps even more so, are implications outside condensed matter physics, for example in hard optimization problems in operational research (travelling salesman, routing and wiring, partitioning of complex tasks etc), and particularly in neural network models of memory in the brain and for the development of new computational devices able to learn from examples, to retrieve memories associatively, to generalize and to exhibit great fault-tolerance (also perhaps to learn how to treat brain disorders).

These studies have also epitomized a new approach to physics which involves not only experimentation and theoretical analysis, but also a new ingredient in the form of computational physics. Here there is not simply the possibility of simulations on the new generations of powerful computers but also the need to 'experiment' on idealized systems, argued to glean the essence of the 'real' experiments whilst having the potentiality of theoretical analysis, and to employ probes for which no analogue exists in real experiments (for example to measure the cross-correlation between two identical systems evolving stochastically independently). The last decade has witnessed a revolution in this area and disordered and frustrated systems have been at the forefront of the arena in which it has taken place.

The current situation on these problems of the cooperative behaviour of systems with quenched disorder and frustration is that the importance of the features have been realized, many specific examples and classes of example identified, several new concepts appreciated and a number of new techniques developed. However, there is still a great deal to be learned and applied to other systems, to other aspects, to greater 'reality', to greater rigour, to the development of theoretical, experimental and computational techniques beyond the current restricted range. Some of the questions can be formulated, some of the answers guessed at, but many cannot even be anticipated but are expected to exist. It is analogous to the situation of periodic solids of fifty years ago, with the subject recognized and a basic backbone theory in place, but prior to the discovery of a wealth of important second generation phenomena and methodology. It is a subject to watch. There will be important developments in theory, experiment and computer simulation and analysis.

Magnetism and Magnetic Materials

B.D.Rainford,
Southampton University
Southampton, UK.

To give a flavour of recent developments within the area of magnetism research in the UK, I have taken some of the themes of the Magnetism and Magnetic Materials Initiative which was recently set up jointly by the Physics Committee and Materials Science and Engineering Commission of SERC. These are:

(i) Highly Correlated Electron Systems
(ii) Magnetic Thin Films and Multilayers
(iii) New Permanent Magnet Materials

One of the purposes of the MMM Initiative was to stimulate areas of activity where it was felt that UK research had already been left behind by recent developments elsewhere in the world, or was in danger of losing a competitive edge.

(i) Highly Correlated Electron Systems

This title has become something of a catch-all phrase, covering phenomena as diverse as the Fractional Quantum Hall Effect, metal-insulator transitions, narrow band itinerant magnets, heavy fermion and intermediate valence materials and high temperature superconductors. This is not inappropriate, since there is a degree of convergence, at least on the theoretical side, with most of these phenomena being described by various limits of either the Hubbard model or the Anderson model. I will narrow attention, however, onto the itinerant magnets and the heavy fermion/intermediate valence systems.

Itinerant magnets

It is now well accepted that traditional Stoner-Wohlfarth theory adequately describes the ground state of itinerant magnets, and modern first principles band calculations, based on spin density functional form of the local density approximation, do an excellent job of predicting not only the ground state moments, but also the Fermi surfaces of ferromagnetic metals. However the extension of these approaches to finite temperatures fails badly. Predictions of the Curie temperature TC from Stoner-Wohlfarth theory, e.g. for Fe, are out by an order of magnitude. This is because the theory allows the magnetisation to collapse only as the band splitting, and ignores the dominant fluctuations of the magnetisation.

There have been two developments of the last decade or so which have greatly improved our understanding of itinerant magnetism at finite temperatures. The first of these was the development of the "disordered local moment" picture by Hubbard [1] and Hasegawa [2]. Their view is that for time scales long compared to the electron hopping time, the electron spins are correlated to leave the time-averaged magnetisation at a site non-zero. This "local moment" has, at least for times short compared to typical spin fluctuation times, degrees of freedom like those of a classical spin. The thermal excitation of these degrees of freedom leads to the collapse of the magnetisation at temperatures far below the Stoner-Wohlfarth Tc Gyorffy, Staunton et al.[3] have succeeded in marrying this formalism with band theory, using the self-consistent field KKR-CPA method originally devised for disordered alloys. In the case of paramagnetic Fe, their calculated Curie temperatures are within 20% of the experimental Tc~ and calculations of the wave vector dependent susceptibilty x(q) were in good agreement with the semi-empirical approach of Edwards [4], displaying Curie-Weiss behaviour for the static susceptibility. This work must be regarded as a very significant advance in the theory of "strong" itinerant magnets.

The second important development has been in our understanding of <u>weak</u> itinerant magnets. This has been due largely to Lonzarich and his coworkers at Cambridge [5],[6], and has resulted from detailed experimental work, combined with extensions of the selfconsistent spin fluctuation theories of Moriya. Briefly for weak itinerant magnets like Ni_3Al, Ni_3Ga, $ZrZn_2$ and MnSi, which have low Curie temperatures and ordered moments far from saturation, the thermodynamics is dominated by the thermal excitation of long wavelength spin fluctuations. Lonzarich's particular contribution has been to show that for real magnets the spin fluctuation spectrum can be described by very few parameters. These have been determined directly for several different samples from inelastic neutron scattering measurements. When combined with cut-off wavevectors, estimated from band structure calculations and Fermi surface studies, these parameters may be inserted into the self consistent spin fluctuation theory, as developed by Lonzarich and Taillefer [6] to establish a magnetic equation of state for the material concerned. The results of this type of analysis have been truly impressive, with a complete description of both the ground state (e.g. spontaneous magnetisation, Fermi surface and spin wave stiffness) and the finite temperature properties such as the Curie temperature and the temperature dependence of the susceptibility. To have produced such a complete synthesis for this class of materials is, to my mind, a remarkable achievment.

Heavy Fermion and Intermediate Valence Materials

Metallic compounds and alloys containing certain rare earths and

actinides (in particular Ce, Sm, Yb and U) often display highly anomalous magnetic and thermal properties. These phenomena are attributed to the hybridisation between the f electrons and the conduction electrons. In normal rare earths and actinides the f electrons usually display atomic-like properties, with magnetic ground states consistent with Hund's rules. But for these anomalous elements the energy differences between f^n and f^{n+1} or f^{n-1} configurations are small, and the hybridisation with the conduction electrons can cause temporal fluctuations between these neighbouring configurations. This gives rise to the so-called intermediate valence (IV) limit, where the magnetic properties are quite different from those of either configuration: for example Curie-Weiss behaviour of the susceptibility is suppressed and the resistivity shows large anomalies due to the charge fluctuations. Much has been learnt about these materials from inelastic neutron scattering experiments, which give direct information about the spin dynamics. In the IV limit the linewidth of the inelastic spectra is large (typically 5 THz) and weakly temperature dependent. In the limit of weak hybridisation the character of the anomalous properties changes somewhat. Here there is a competition between the hybridisation, which tends to produce a non-magnetic ground state (for the single impurity problem this is just the Kondo effect, which is now well understood), and the RKKY exchange interactions between the f electrons, which tends to stabilise a magnetic ground state. This is a much more complex theoretical problem than the original Kondo problem, since there is a magnetic "impurity" at every lattice site, and in the ground state at least, the hybridised f electrons must form Bloch states. This is seen experimentally: at high temperatures these materials behave like a collection of independent Kondo impurities with large resistivity anomalies etc. At low temperatures, however, the resistivity drops to a low value, indicating the onset of a coherent ground state with Fermi liquid like properties. In this state γ, the coefficient of the electronic specific heat can be enormous, of the order of several Joules per mole K^2. Such a value is two orders of magnitude larger than that expected for conventional metals, and suggests that the quasiparticles responsible have effective masses of the order of 100 times the electron mass (hence the nomenclature "heavy fermion"). For some time it was not clear whether this attribution of the experimental phenomena to heavy quasiparticles was correct, but in the last few years there has been the first direct evidence of their existence, through measurements of the de Haas-van Alphen effect on pure single crystals. These have been mostly due to two UK groups under Springford (Sussex, now moved to Bristol) and Lonzarich (Cambridge). In dHvA measurements the effective masses of the quasiparticles can be inferred from the temperature dependence of the amplitudes of the oscillatory components. In both $CeCu_6$ and UPt_3 effective masses of the order of 100 me are indeed found for certain cyclotron orbits. These measurements require high magnetic fields and

Condensed Matter Physics: A Quantum Many-Body Theory Viewpoint

Raymond F. Bishop
Department of Mathematics
UMIST

The main points discussed in my talk and the ensuing discussion can be summarized in terms of the following principal items:

1. Background Perspective

A broad overview was presented in terms of the main emphases and the key developments which have been presented and discussed at the various meetings to date of the series of *International Conferences on Recent Progress in Many Body Theories, viz.*

0th (Rome; 1972), 1st (Trieste; 1978), 2nd (Oaxtepec, Mexico, 1981)
3rd (Altenberg, W. Germany; 1983), 4th (San Francisco, USA;1985)
5th (Oulu, Finland; 1987), 6th (Arad, Israel;1989).

2. Current Status

Several very powerful, microscopic, *ab initio* techniques of quantum many-body theory (QMBT) now exist which are: *widely applicable; very accurate; capable of systematic improvement; able to predict and transcend phase transitions.* Foremost among these are:

the coupled cluster method (CCM), and the correlated basis function (CBF) method.

Applications of the CCM, for example, have been made to many diverse areas of condensed matter theory writ large. We review the highlights of several of these:

(i) quantum chemistry: where the CCM is now the method of first choice. It provides a factor > 10 (and often » 10) saving in accuracy and/or computer time over alternate methods. State-of-the-art calculations involve molecules with < 80 active electrons are now on the verge of being able to treat molecules of biological interest. For the first time, *chemical accuracy* is now achievable (i.e., correlation energies per particle correct to 1 mH).

(ii) atomic physics: Note for example the recent great interest to look for parity violation in atoms, and the implied need for *very* accurate wavefunctions implies that CCM is widely recognized as best candidate.

(iii) nuclear physics: CCM now provides the best available calculations for closed-shell nuclei and neighbouring open-shell nuclei with 1 or 2 valence particles or holes. for the first (and only) time in nuclear physics, *ab initio* QMBT calculations on finite nuclei with realistic, best available, phenomenological NN potentials are fully converged.

(iv) quantum field theories: e.g., pion-nucleon models; f^4 -field theory in (1+1) and (2+1) dimensions (in both vacuum and soliton sectors).

(v) electron gas: CCM now provides best (by far) available microscopic results, by comparison with Green function Monte Carlo calculations, for this most well-studied of all quantum many-body problems giving correlation energies per particle accurate to < 1 mRy over the entire metallic density range ($1 < r_s < 6$).

(vi) anharmonic oscillators (and spins): CCM provides best available discussion of asymptotic properties yet given; indeed, best overall description of *any* nontrivial field theory.

(vii) electron lattice models: e.g., cyclic polyenes; polyacetylene; Hubbard model; Pariser-Parr-Pople model.

(viii) spin lattice models: recent work, but CCM already showing very good results for e.g., solid He phases; l-d and 2-d quantum antiferromagnets (e.g., XXZ model) for spin S = 1/2 and S > 1/2.

(ix) positron annihilation in metals and alloys: CCM provides a uniquely powerful gauge-field treatment of the theory behind this important experimental technique.

(x) quantum hydrodynamics: of strongly-interacting condensed Bose fluid. CCM provides a *complete* microscopic description, of which the lowest order approximant is Gross-Pitaevskii theory.

3. Emerging Trends

We note a number of possible future areas in which *ab initio* techniques of microscopic QMBT might play a role. These include the following:

(i) High-T superconductors and other novel ("unorthodox") materials:

Developments will probably come from a merging of ideas from theoretical many-body physics with theoretical (especially quantum) chemistry ensuring that CCM is especially well placed.

(ii) Monte Carlo techniques: particularly extensions to deal more efficiently with fermions, e.g., via diffusion (DMC), Green function (GFMC), path-integral (PIMC) versions.

(iii) "Complex systems": e.g., spin glasses; neural nets; associative memories; collective computation; computational structures; cellular automata; self-replicating and self-governing systems; adaptive systems. These are all characterized by: nonlinear and dissipative behaviour, and (often) asymmetry in the interactions between the components or relevant sub-units giving distinctly different features from both classical and quantum-mechanical many-body systems (e.g., impossibility of a Hamiltonian description often?). Nevertheless, one is still tempted to think in terms of *collective modes, quasiparticles,* etc. It is still an open question as to whether QMBT can play a key role here and/or be inspired itself into new directions. Developments may well come from a merging of ideas from various branches of theoretical physics with theoretical (neuro-)biology and theoretical computational science.

(iv) Quantum field theory: particularly QCD (either in discretized lattice version or original continuum theory). In latter regard, for example, we recall Ken Wilson's recent remarks concerning the usefulness of going back to methods in quantum chemistry for inspiration. He had configuration-interaction (CI) ideas in mind, but CCM must be a much better candidate.

(v) Particular problems in quantum chemistry: e.g., (a) muon-catalyzed fusion; (b) catalysis (understanding of mechanisms and design of new catalysts).

(vi) Spin-polarized quantum systems: a recent revival of interest in this area, e.g., possible imminent experimental realization of H$\emptyset$ and D$\neq$ at 'quantal' densities and temperatures.

(vii) "ConventionaL" condensed matter: a recent revival of interest in several areas, largely driven by the advent of experimental data from inclusive inelastic scattering of weak probes, e.g. *(a) liquid ^{3}He, ^{4}He, and their mixtures* — from deep inelastic [i.e., high (q,w)] neutron scattering at IPNS facility, Argonne, and elsewhere; *(b) nuclei* — from quasielastic electron scattering at SLAC, NIKHEF, (CEBAF), and elsewhere.

(viii) "Marriages" between different QMBT techniques: several now on the horizon involving, e.g., CBF method, CCM, parquet theory, density functional theory. The hope is that the offspring will have the best and most powerful features of both parents.

(ix) Nanometer-scale structures and femtosecond-scale dynamics: e.g.,

quantum wires; quantum dots; atomic clusters (and associated 'magic numbers', opto-electronic properties, possible use in catalysis); advent of very fast laser facilities (e.g., at University of California, Irvine, and elsewhere).

(x) Quantum optics as a microscopic QMBT problem: e.g., already 'squeezed' (2-photon) coherent states find a simple and natural description via the CCM implying real possibilities offered to describe 'hypersqueezed' (n-photon, n > 2) coherent states in a completely novel fashion, unlike previous (unitary) attempts.

4. The Current UK and International Scenes

A wide-ranging discussion centred on the following two main themes:

(i) Funding Patterns
In the UK, as in USA and elsewhere, there has already been considerable pressure to establish large centres for focussed, mission-oriented research (e.g., Interdisciplinary Research Centres), with expected potential payoffs. This has led to continuing debate over "Big Science" versus "little science", and over the likely outcome that individual grants for basic ("blue skies") research have suffered, and will continue to do so unless recent trends are reversed. There was considerable feeling that at least for the areas of condensed matter physics and QMBT under discussion, the current policies were driving research in ways that exposed inherent weaknesses (e . g., of overspecialization; fragmentation; over-management; demands for predictability, goals, milestone achievements). While these aims and policies may beneficial in some areas, they could not easily be seen to be so in our areas.

(ii) Manpower, etc.
Many areas within physics (and other sciences) are rapidly becoming 'endangered species'. This seems to be true in the UK, USA, and elsewhere. In this regard, 'cross-links' between traditional areas become increasingly important, and should be fostered. QMBT and condensed matter physics in general is particularly well (uniquely?) placed in this regard.

5. Specific Comments

(i) The UK is still strongly represented at the phenomenological level of work in this area.
(ii) The UK has a strong experimental programme in traditional condensed matter physics, with high international profile.
(iii) The UK has specific (unique) expertise at some levels of microscopic QMBT. The CCM is a prime example.

(iv) The UK has strength in theoretical (quantum) chemistry (and atomic
physics), which may become increasingly useful in the future.
(v) UK groups, both theoretical and experimental, already have many active international collaborations.
(vi) There is particular and urgent need to develop and encourage the 'overlap areas' of cross-disciplinary research, all of which are likely to become of increasing importance.
(vii) There is an urgent need to evolve structures for ongoing funding and support that go beyond the pump-priming level, in order to put both existing local overlaps and international collaborations on a firmer long-term footing, but with flexibility of response retained.

6. Possible Applications

These have already largely been covered or hinted at in earlier parts of the report. Areas include: atomic physics; quantum chemistry (catalysis, etc.); quantum biology; quantum pharmacology (designer pharmaceuticals, etc.); materials science (new materials, catalysts, superconductors, etc.).

The most important single feature is our ability to "bridge" and transcend other more traditional fields. We have much existing expertise with various extremely powerful, general-purpose tools (e.g. CCM); a great deal of experience from using them widely elsewhere; and a consequent faith in their potentially even wider applicability.

Superconductivity- an overview

Colin E Gough
Superconductivity Research Group
University of Birmingham,
Birmingham, B15 2TT.

1. Background.

Superconductors have been known for over 75 years and form the basis of a fairly mature technology at liquid helium temperatures worth about $300M/year. This is largely made up of superconducting magnets for elementary particle accelerators and for MRI, which constitutes the only significant commercial current application, though the Japanese have an extensive active programme using such magnets for magnetic levitation for trains, ship propulsion and magnetic energy storage. The USA and Germany have rather smaller programmes in these areas. Although the UK was amongst the first to exploit conventional superconductors - IMI still produce a large fraction of the superconducting wires used in MRI magnets- it effectively dropped out of superconducting materials research in the 1970s, with only a low level of research activity in industry and in a small number of University research groups.

The discovery of the layered cuprate superconductors by Bednortz and Muller and the subsequent discovery by Chu and Wu of the YBCO variant, superconducting well above liquid nitrogen temperatures, greatly enhanced expectations for a wider technological exploitation of superconductors, quite apart from creating one of the largest research initiatives ever known, with well over 12,000 scientific publications within the first three years. The understanding and exploitation of these new materials has to involve an interdisciplinary activity with physicists, chemists, materials scientists and engineers alongside each other. In addition, early exploitation has often involved a large degree of collaboration between universities and industrial companies. Industry is even shorter of researchers with any significant experience of superconductivity than the universities, where it remains difficult to attract and retain the brightest students because of relatively poor starting salaries and career structures.

2. Current status of research on HTCs

It is now well established that HTC superconductors owe their characteristic properties to the essentially 2-dimensional nature of charge carriers in the CuO planes generic to all HTC superconductors. There are now around a dozen or so different cuprate structures which exhibit HTC. Most compounds involve an antiferromagnetic insulating phase, which

on doping undergoes an insulator to metallic transition exhibiting superconductivity. The majority of HTC superconductors are p-type, in which substitutional doping or control of oxygen stoichiometry (as in $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_{6+x}$) is used to control the electronic doping of the CuO planes. On increasing doping (x >O), the AF Neel transition temperature decreases rapidly to zero at which point superconductivity appears, though in the La-compounds there appears to be an intermediate spin-glass phase.

In these compounds correlations between electrons in the CuO planes are extremely important. In the normal state this is believed to lead to the formation of what has become known as a "marginal" fermi-liquid, or "electron-slush", as Bob Schrieffer more vividly chooses to call it. This results in anomalous properties in the normal state, with a highly anisotropic intrinsic resistivity with a rather accurate linear increase with temperature in the high conductivity direction parallel to the planes. X-ray absorption measurements suggest that electron transport in the CuO planes is largely via "holes" at the oxygen positions in the CuO planes. Angular resolved photo-electron emission spectroscopy (ARUPS) measurements are consistent with the existence of a distinct Fermi-surface feature. Electron lifetimes on moving away from the Fermi-surface appear to vary as $E-E_F$, which is an important features of the marginal Fermi-liquid model. In some recent remarkable scanning electron tunnelling measurements, claims to obtain I/V characteristics at individual atomic positions within the BISCCO structure. On the BiO planes the measurements suggest a semi-conducting gap at the fermi-surface, whereas measurements on the CuO planes are again consistent with the existence of free-carriers with marginal Fermi liquid properties.
ARUPS measurements also provide the most convincing evidence yet for the opening up of an energy gap on entering the superconducting state. So far such measurements have been restricted to BISCCO, which cleaves conveniently between the BiO planes, so that the outermost superconducting CuO layers are largely protected. Nevertheless, recent unpublished IBM measurements suggest that the gap-feature is confined to only 10% of the cleaved surface. Furthermore there remain some uncertainties about published measurements of angular resolved photo-emission of electrons, as taken at their face value they imply non-conservation of electronic states, which is unphysical. Nevertheless, this has not inhibited theorists from developing models to explain the results! Further refinements of experimental techniques in this area are likely to provide significant additional information about the nature of the superconducting transition, and should answer the important question of whether or not intrinsic low-lying electronic states exist within the gap, as most current tunnelling measurements on HTCs appear to imply.

Without a proper understanding of the electronic properties in the

normal state, it is scarcely surprising that a satisfactory microscopic theory for HTC superconductivity does not yet exist. It is known from Birmingham flux-quantisation experiments that electrons in HTC superconductors are paired and that such pairs retain their quantum mechanical phase-coherence on passing into a conventional superconductor, where the pairing is well-described within the BCS theory via an indirect phonon-interaction. Such a mechanism gives an upper limit for superconductivity of around 35K - far too low to describe superconductivity at 125K in the 3-CuO layer thalium compound, the highest Tc yet achieved. BCS may still be an appropriate model but with a different pairing mechanism. Interaction via the localised electron spins on the Cu atoms is an obvious candidate, as superconductivity appears to be intimately related with a transition from the AF state of these spins. It is also likely that the effective 2-dimensionality plays an important role in determining Tc Other more exotic routes to superconductivity have been suggested, such as models based on Anderson's RVB idea and on anyons, which are closely related to the electron states introduced by McLaughlin to describe the fractional Hall effect. However, although two groups have reported parity violation in optical measurements, consistent with an anyon model, in the most accurate optical dichroism measurements made to date (at Stanford) no such effect was observed. Most current theoretical work within the framework of conventional mechanisms are based on variants of the Hubbard model in 2-dimensions, which has provided an accurate description of the AF properties in the insulating phases. HTC has provided a dramatic stimulus towards developing powerful analytic and computational techniques for tackling problems involving strongly interacting electrons. In Bob Schrieffer's words, "HTC superconductivity is writing the Physics text-books of the 1990s"- meaning the physics of strongly interacting electrons in the widely diverse systems of magnetic, ferroelectric, dielectric and superconducting materials involving transition metal oxides.

The technological potential of HTC superconductors requires not only high Tc's but also large supercurrent densities in the presence of large magnetic fields, which may be self-induced. These properties are controlled by the coherence length, the effective size of the electron-paired state. In HTCs the coherence length is already short within the CuO planes (20-30 A) but is only of atomic dimensions perpendicular to the planes. This accounts for the very large magnetic fields required to destroy superconductivity in these materials (>100 T) but creates serious problems when it comes to developing materials suitable for applications. In particular, with such a short coherence length, changes in stoichiometry on an atomic scale can effectively destroy superconductivity, a problem that is extremely serious if surfaces are involved, as in junction technology. Furthermore, a short coherence length means that the energy required to pin a flux line (a requisite for zero-resistance in the

superconducting state) is rather small. At elevated temperatures, thermal excitation leads to thermally activated voltage states and the creep of flux out of a superconducting magnet.

When the cuprate superconductors were first discovered it quickly became apparent that in their sintered form few applications were possible because the superconducting properties were largely suppressed by fields not much larger than that of the Earth's field. This degradation results from weakly superconducting regions connecting the sintered grains - the so called weak-links of granular material. Many Jeremiahs were quick to forecast a future for HTCs parallel to that of cold-fusion. However, over the last two years there have been remarkable increases of many orders of magnitude in the performance of HTCs in bulk, thick and thin film form, including the ability to support large currents in quite substantial fields (typically ~1 T and exceeding 1O T in some forms). At liquid nitrogen temperatures, applications of HTCs can now be confidently predicted in several areas. At liquid helium temperatures, HTC wires have already been demonstrated with superior properties to conventional superconductors.

Several tricks have been invoked to optimise the superconducting properties. The simplest was to align individual grains within a bulk ceramic with the CuO planes parallel to the current flow, minimising the problem of poor supercurrent flow perpendicular to the CuO planes. Bulk material can also be dramatically improved by largely eliminating weak-links between the grains by a high temperature processing route involving melting (melt-textured material). Such material has superconducting properties in the laboratory, which already approaches the requirements for the low power end of engineering applications. The problem now is to form coils from such material. This is essentially a materials science problem, where steady progress over the next few years can confidently be expected. Liquid nitrogen cooled melt-textured YBCO has already been demonstrated levitating kg weights, so that essentially frictionless magnetic bearing are already possible. In Birmingham and at ICI, we have also produced melt-textured grain aligned thick films, with technologically promising properties for low current and microwave applications. It is also interesting to note the recent ICI/Hammersmith Hospital demonstration of the use of a sintered extruded YBCO wire to replace the Cu rf pick-up coil in a MRI machine. This increased the signal to noise ratio by a factor of 4 allowing the desired brain scan to be achieved in half the time normally taken. Doubling patient throughput or the use of less powerful magnets could have considerable commercial implications in the running of such facilities.

However, the area where most progress has been achieved is in thin-films, where epitaxially grown thin films have been demonstrated with critical current densities in excess of 107 Acm-2 at liquid nitrogen temperatures,

within a factor of three of the maximum possible intrinsic limit, with little degradation in magnetic fields up to fields of order SOT. Such films are already finding commercial application as microwave filters, where HTC superconductors outperform liquid nitrogen cooled copper below about 100 Ghz . Passive microwave devices are already the first commercial applications of HTCs. Superconducting antennas were quickly demonstrated by Birmingham, cavities demonstrated by several groups and many coplanar and other transmission line devices are under active development in laboratories around the world.

The final area of practical importance is SQUIDs, in which the requirement of phase coherence around a superconducting ring leads to devices with a sensitivity based on the quantum of magnetic flux (h/2e). Such rings have to incorporate one or more weak-links. Early devices were based on bulk material making use of the intrinsic weak-links between grains. Despite their crudeness, bulk SQUIDs have been developed with sufficient sensitivity to monitor the magnetic field from the heart. Early thin-film SQUIDs also made use of the weak-links between the grains that formed when the films were annealed in oxygen. Koch and colleagues at IBM achieved a sensitivity in a Tl-based thin film granular dc SQUID comparable to commercially available liquid helium cooled rf SQUIDs. Very recently, Chaudari's IBM Group have succeeded in making a SQUID using an epitaxial HTC film (with no intrinsic weak-links) grown across a substrate bicrystal junction, forming a well-controlled weak-link region. The only problem remaining is to develop a multi-layer film technology so that coupling coils with cross-overs can be incorporated into the fully operational device. This latter problem has almost been solved by the Berkeley/Conductus group and commercially available liquid nitrogen cooled SQUIDs should, in principle, be available within the next year or so. Although the performance of liquid nitrogen SQUIDs is unlikely ever to match that of liquid helium cooled SQUIDs (because of thermally activated noise), quantum energy sensitivity of h/Hz is in principle achievable.

3. Future trends.

Considerable improvement of superconducting properties of HTC superconductors in all forms- bulk, thick and thin films, single crystals, can confidently be predicted over the next few years. However, it is not possible to predict higher Tcs, as HTC is to date confined to the cuprate superconductors, where we appear to have already reached the maximum possible. The recent Japanese report of HTC in a vanadium oxide, if confirmed by other groups, would be very exciting, as there is no intrinsic reason why higher critical temperatures should not be achieved.

Scientifically we can expect considerable progress in our understanding of

both normal and superconducting properties from more refined and novel experiments and in further advances in theoretical methods for dealing with systems involving strongly interacting electrons.

A particularly interesting recent development has been the demonstration by at least three groups of the growth of heterostructures with alternating layers of superconducting and insulating material containing small numbers of unit cells in each. Indeed, structures have been grown with a single unit cell of YBCO sandwiched between several layers of the insulating PrBCO compound. Superconductivity was observed at 20K, demonstrating superconductivity in a truly 2-dimensional structure. Such heterostructures have obvious potential for device applications including a three-terminal HTC transistor, which could revolutionise superconducting electronics.

4. Strengths and weaknesses of UK HTC activities.

The UK optimise the effectiveness of a relatively small (by USA or Japanese standards) budget for HTC activities by having a coordinated activity under the joint SERC/DTI/MOD National Committee for Superconductivity. A special centre for superconductivity research (IRC-Interdiscipinary Research Centre) was established at Cambridge and there is a national coordinator - currently Prof. Gordon Donaldson, Dept. Physics, University of Strathclyde. The SERC supports several other large groups on renewable 4-year rolling grants (Birmingham, Imperial and Warwick, shortly to be joined by Oxford and Southampton) and supports several smaller groups elsewhere. The DTI has a special HTC initiative, in which 50% funding is provided for collaborations involving at least 3 industrial partners.

The UK had a number of early successes in science and early applications (several involving Birmingham) and continues to produce some of the best structural data based on the world-class Rutherford-Appleton neutron diffraction facility. In the industrial sector ICI are world-leaders in their work on extruded bulk ceramics and thick films, established largely by their ability to interact with a large number of research laboratories in the UK and throughout the world.

In the important area of thin films, the UK academic programme has largely failed to match progress in Japan, the States and Europe, largely because the groups involved are too small to be properly effective and because potentially, groups like Jan Evett's in Cambridge failed to obtain the support necessary to build on their early successes in this field. However, the UK does have a world-class thin-film facility supported by the MOD at RSRE-Malvern, with a very strong team of 7 full-time researchers. I would expect this group to match any in the world in terms

of future developments.

It is easy to point to weaknesses but not so easy to suggest remedies. In the early stages of HTC the academic sector was desperately short of the appropriate experimental facilities for conducting world-class research. This has now been partially rectified via special equipment allocations through the SERC but several important groups still lack the equipment they deserve. There is also a continuing shortage of young UK researchers, largely as a result of poor salaries and career prospects within the universities, which makes recruitment difficult relative to many other professions. There is also a shortage of senior scientists in academia and industry with relevant experience in superconductivity. This is particularly marked in theory, where so many of our brightest solid-state theoreticians active in the field of superconductivity emigrated to the States long ago - Emery, Doniach, Littlewood, Thouless, Kosterlitz, Legget to name but a few.

In the industrial sector, few companies are willing to invest in research that is not seen to have a visible return within a one or two year period, whereas it is obvious that HTC must be considered on a much longer times scale. The DTI has made appreciable matching funds available to industry (up to $8M over 3 years) but it is not yet all taken up. Amongst those firms taking part in this initiative, several have had to withdraw because of changes of company policy and industrial take-overs. However, on the bright side at least three large firms - ICI, GEC and Cooksons - are making a serious commitment to HTC. The fear is that an overall lack of confidence on the industrial side may influence the UKs attitude towards HTC in general, making it more difficult to obtain the funds to support an already seriously constrained academic research programme through the SERC.

5. Summary.

It is important to emphasise that the above is a highly personal view on what I consider to be the main interests and problems in HTC and that, in particular, my views on the UK scene may differ appreciably from many other UK researchers in the field. However, as should be clear, I believe that HTC superconductivity will continue to be at the focus of mainstream condensed matter physics and materials science research for at least the next decade and that during this time we can confidently expect a number of significant commercial applications at liquid nitrogen temperatures. Relative to the total world effort in HTC the UK has made a significant contribution to scientific and materials advances and to engineering applications and will continue to do so.

It is likely that future advances will be stimulated by international

collaborations and I would welcome any support that could be provided to strengthen links with a number of research laboratories in the USA by way of visits and collaborative programmes.

Algebraic and Group Theoretical Methods
in Condensed Matter Physics : a Peroration

Mario G. Rasetti
Dipartimento di Fisica, Politecnico, Torino, Italy
and
I.S.I., Institute for Scientific Interchange, Torino, Italy

In recent years algebraic and group theoretical techniques have more and more deeply entered the theory of condensed matter physics, in forms different from the conventional (connected mainly to symmetry) that promise to become novel, very powerful, tools both in tackling in exact or closer to exact way a wide class of problems so far solvable only in perturbative way, and in providing the means to describe in simple form interactions otherwise cumbersome and complicated.

In this note, I want to review briefly two fields in which this has already happened, using them as paradigms for a more general assessment of the methodology.

The first example comes from quantum optics, and concerns the construction (mathematical as a premise to physical) of quantum states for which the noise content for some of the canonical dynamical variables is kept below the bounds imposed by the uncertainty principle: the so called *squeezed states*. Since the very beginning [1],[2], it was realized that in the simplest instance when only two-particle processes were taken into consideration, the particles being bosons (*e.g.* photons), such states could be related to an algebra : $su(1,1)$. The generalization of this simple observation, following the comprehension of the property that those squeezed states were indeed the generalized coherent states for $su(1,1)$, has allowed us to construct a whole new wide class of squeezed states, related as well to $su(2)$, and $su(n)$ [3]. A truly interesting progress was successively possible by basing the construction of such new states not only on the fundamental representations of the corresponding algebras but on some of their nonlinear realizations. Resorting, among the latter, to Holstein-Primakoff's both in its conventional and in its multi-boson representations (this in terms of the k-boson isomorph of the Weyl-Heisenberg algebra), has led then to quite new sets of squeezed states, controllable in much finer way than the conventional, and very rich in structure [4],[5]. It has also allowed to overcome a long standing difficulty, connected with the non-analyticity of the corresponding states in the Fock space, of "naturally"

extending to many-photon processes the construction of squeezed states based on two photons[6].

As physically relevant output of this approach to squeezing in a multi-boson frame it is worth mentioning the introduction of the notion it led to of fractional photons[7], a concept which has recently allowed us to fully understand the structure of phase-number squeezed states[8],[9],[10], suggesting as well possible venues for their physical realization.

Another, very recent, product of the same scheme is the extension of the whole construction of coherent states to the Hopf algebras[11],[12] (customarily, and somewhat improperly referred to as quantum groups), which not only exhibit squeezing in the conventional way, but lead as well to different notions of weak and strong squeezing[13]. Quantum group coherent states have indeed found a first very interesting application in quantum optics, where they have been utilized to handle the dynamics of a generalized Jaynes-Cummings model (describing a two-level atom in a radiant cavity), in which the interaction between atom and radiation field is non-linearly dependent on the field intensity[14]. It is interesting to notice that such an application was fostered by the observation that the Jaynes-Cummings model in its originary form has a dynamical algebra which is a $\mathbb{Z}_2$-graded (*i.e.* super-) algebra, a property that remains valid – with a different, wider, dynamical superalgebra – even in the case when the field self-energy is included in the model[15].

The second example comes from condensed matter physics, and concerns the application of the notion of dynamical algebra to fermion systems in the framework of the Fermi linearization scheme[16]. There are several interesting features stemming out of the latter, which are worth further extended work. To begin with, the dynamical algebras one obtains in that scheme can be superalgebras, which leads to the introduction of a set of order parameters valued in the even sector of a Banach-Grassmann algebra (the latter generated by the non-orthogonality of the holon and spinon states) describing in a novel way spatial correlations among the electrons (or holes) in the lattice. The ensuing scheme is far reaching : on the one hand one finds that both the ground state and the excited states of an interacting fermion system (described *e.g.* by the Hubbard hamiltonian or extension thereof) can be represented – in the cluster approximation – as generalized coherent states for the dynamical superalgebra[17],[18],[19],[20],[21]. This in turn not only allows one to write explicit self-consistency equations but has on the other hand very promising consequences. For a system prepared in an initial state which is a super-coherent state, as the hamil-

tonian is an element of the superalgebra, and hence the time evolution operator is an element of the corresponding supergroup, the representative point of the system itself is constrained, as it evolves in time, to remain enbedded in the coherent state manifold. The latter in the case of a superalgebra is a supermanifold, whose topology – when the algebra of the fermionic order parameters is not purely Grassmann, but is endowed with the extra-relations [18] stemming from the requirement mentioned above – is nontrivial. It is just this last property that makes the effective action whereby one can represent the quantum propagators on the coherent states manifold in terms of Feynmann path integrals to contain terms of global topological origin. We expect the latter to be identifiable with Chern-Simons terms, and the corresponding field theory to be identical (but derived from a microscopic hamiltonian !) with that of anyons. Another promising consequence of the fermi linearization combined with cluster expansion and with the existence of dynamical superalgebras (for an n-site cluster, and a conventional Hubbard hamiltonian, this is $\bigoplus_{\alpha=1}^{2^n} u(n|1)_\alpha$, the $u(n|1)_\alpha$ being 2^n copies of the superalgebra $u(1|1)$) is that one can ask oneself wheter the theory can be cast in supersymmetric form; that is wheter one can construct, in the fermionic sector of the dynamical superalgebra a "charge" operator Q, such that $Q^2 = 0$, and the hamiltonian $H = \{Q, Q^\dagger\}$, which annihilates the ground super-coherent state $|\zeta_{g.s.}>$, $Q|\zeta_{g.s.}>= 0$. It is most interesting that this turns out to be impossible for the conventional Hubbard model, but can be realized for the KSSH (Kivelson, Schrieffer, Su, Heeger) model, provided [17] the 2-d lattice over which this is defined has the structure which is typical of the copper-oxide planes for the YBaCuO high-T_c superconducting compounds ! The interest of this latter observation is further increased by the feature that in the supersymmetric form the model exhibits non-zero pairing order parameter, whereas it is no longer supersymmetric (supersymmetry is spontaneously broken) when such order parameter vanishes. A self consistent temperature analysis, performed so far only on small clusters [22], allows to compute the critical temperature dependence on the on-site Coulomb repulsion energy and on the hopping amplitude. It should be noticed that in ref. [16] it was shown how also conventional superconductive phase transition can be thought of as sponaneous breaking of supersymmetry. It may be also worth recalling that the dynamical algebra structure has recently lead us [23] to an exact solution – holding in the case when spin-flip hopping processes are given the same amplitude as parallel-spin hopping processes – of the KSSH model [24].

Further research along all these directions should be encouraged : I do believe that it will pay dividends to invest also in *ad hoc* programs aimed to develop specific

languages for symbolic manipulation, whereby part of these efforts could be tackled in authomatised way.

References

[1] D. Stoler, Phys. Rev. **D 1**, 3217 (1970)

[2] H.P. Yuen, Phys. Rev. **A 13**, 2226 (1976)

[3] J. Katriel, A.I. Solomon, and M. Rasetti, Phys. Rev. **D 35**, 2601 (1987)

[4] G. D'Ariano, J. Katriel, M. Rasetti, and A.I. Solomon, Phys. Rev. **D 34**, 2332 (1986)

[5] G. D'Ariano, J. Katriel, M. Rasetti, and A.I. Solomon, J. Opt. Soc. Am. **B 4**, 1728 (1987)

[6] G. D'Ariano, M. Rasetti, and M. Vadacchino, Phys. Rev. **D 32**, 1034 (1985)

[7] J. Katriel, M. Rasetti, and A.I. Solomon, **D 35**, 1248 (1987)

[8] G. D'Ariano, J. Katriel, S. Morosi, M. Rasetti, and A.I. Solomon, Phys. Rev. **D 36**, 2399 (1987)

[9] G. D'Ariano, and N. Sterpi, Phys. Rev. **A 39**, *1860 (1989)*

[10] G. D'Ariano, Phys. Rev. **A 41**, 2636 (1990), and *Number-phase Squeezing through Nonunitary Scaling*, University of Pavia Preprint, october 1990, *to be published* Phys. Rev. **A**

[11] J. Katriel, and A.I. Solomon, J. Phys. **A**: Math. Gen. *to be published*, and *Generalized q-bosons and squeezed states*, The Open University Preprint, december 1990

[12] M. Rasetti, *Quantum Group Coherent States*, in *Integrable Systems in Statistical Mechanics, Braids, Knots, and Quantum Groups*, M. Carfora, and A. Marzuoli, eds.; World Scientific Publ. Co., Teanek, 1990

[13] E. Celeghini, M. Rasetti, and G. Vitiello, Phys. Rev. Lett. *to be published*, and *On Quantum Groups and Squeezing*, University of Florence Preprint, november 1990

[14] M. Chaichian, D. Ellinas, and P. Kulish, Phys. Rev. Lett. **65**, 980 (1990)

[15] C. Buzano, M. Rasetti, and M.L. Rastello, Phys. Rev. Lett. **62**, 137 (1989)

[16] A. Montorsi, M. Rasetti, and A.I. Solomon, Phys. Rev. Lett. **59**, 2243 (1987)

[17] A. Montorsi, M. Rasetti, and A.I. Solomon, Intl. J. Mod. Phys. B 3, 247 (1989)

[18] A. Montorsi, and M. Rasetti, Mod. Phys. Lett. B 4, 1289 (1990)

[19] A. Montorsi, M. Rasetti, and A.I. Solomon, *Spectrum Generating Superalgebra for a Fermi Linearised $\mathcal{N}$-cluster Hubbard Model*, in *Group Theoretical Methods in Physics*, V.V. Dodonov, and V.I. Man'ko, eds.; Springer-Verlag Lecture Notes in Physics, Berlin, 1990

[20] A. Montorsi, and M. Rasetti, *The Cluster Fermi-Linearized Hubbard Model*, in *Dynamical Symmetries and Chaotic Behaviour in Physical Systems*, L. Franzoni, G. Maino, and M. Pettini, eds.; World Scientific Publ. Co., Teanek, 1990

[21] L.R. Evangelista, A. Montorsi, and M. Rasetti, *Spectrum of the Fermi-Linearized Extended Hubbard Model on a Dimer*, in *Microscopic Aspects of Nonlinearity in Condensed Matter*, A.R. Bishop, and V. Tognetti, eds.; Plenum Press, New York, 1990

[22] R. Livi, and A. Montorsi, Intl. J. Mod. Phys. B, *to be published*

[23] A. Montorsi, and M. Rasetti, Phys. Rev. Lett., *to be published*

[24] S. Kivelson, J.R. Schrieffer, W.P. Su, and A.J. Heeger, Phys. Rev. Lett. 58, 1899 (1987)

Appendix I:

A Note on the Funding of "Mainstream" Physics in the United Kingdom

B.D.Rainford, Physics Department, Southampton University

1. The sources of funding

1.1 The Research Councils

The funding of basic and strategic science in the UK is supported by the four Research Councils, namely SERC, AFRC, MRC and NERC. SERC, the Science and Engineering Research Council, funds the whole of physics, engineering, chemistry, mathematics and "core" biology. The more applied aspects of biology come under the AFRC (Agriculture and Food Research Council) and MRC, the Medical Research Council. Geology, geophysics, oceanography, meteorology etc. come under NERC, the Natural Environment Research Council. There is one further body, ESRC, the Economics and Social Research Council, which supports the social sciences. The Research Council structure is headed by ABRC, the Advisory Board for the Research Councils, which coordinates bids for funding to the Government under the annual PES (Public Expenditure Survey) rounds, and determines how the science vote is divided between the Research Councils.

1.2 Science and Engineering Research Council

Within SERC there are four Boards, covering the main areas, namely Nuclear Physics Board, Astronomy and Planetary Science Board (APS), Science Board and Engineering Board. Science Board covers biology, chemistry, mathematics and "mainstream" physics; the latter means in practice atomic physics (including laboratory based plasma physics), optics and condensed matter physics. These four Boards have roughly equal budgets. Physics as a whole, then, has the lions share, dominated by the large "big science" components of the Nuclear Physics and APS Boards with their associated international subscriptions, e.g. to CERN, ESA etc. This is shown in fig.1, where the lower part refers to total expenditure, while the upper part shows the drift in "domestic" expenditure (i.e. excluding international subscriptions) over the four year period 1984-88. There has been a policy within SERC, over the last decade, to switch funding away from astronomy and nuclear physics towards "strategic science and engineering". This has amounted to a shift of about 5% of total expenditure, and severe pressure on international subscriptions.

Within Science Board there are five subject committees, namely Biological Sciences, Chemistry, Mathematics, Physics and Science-based Archaeology. There are also two committees associated with the Science Board central facilities, namely the Synchrotron Radiation Facility Committee (SRFC) and the Neutron Beam Radiation Facility (NBRC). All the subject committees consider applications for research grants which are submitted twice per year for the deadlines of 15 September and 15 February.

1.3 Physics Committee and MSEC

Grant applications to Physics Committee are dealt with by the two subcommittees X and W. X deals with atomic physics, lasers and optics, while W copes with most of condensed matter physics. The process of appraisal of grants is based on peer review: both the grant referees and the subcommittee members are largely drawn from the appropriate university academic community.

One of the unsatisfactory aspects of the SERC Board structure is that areas of science which straddle two Boards are sometimes inadequately funded. The obvious example was material science, which spans an enormous range of activity from the fundamental physics of alloy properties to process engineering. Until the mid 1980's much of material science was funded from Engineering Board, and there was a widespread feeling of dissatisfaction with this arrangement within the material science community. This structural problem was addressed by the Day Committee, under Prof. Peter Day FRS. Rather than set up a separate Materials Board, it was decided to establish the Materials Science and Engineering Commission (MSEC) as a separate body, but receiving its funding jointly from Science Board and Engineering Board. This has led to the setting up of a number of subcommittees dealing with specific areas of activity, including some which were previously funded through Physics Committee. The MSEC subcommittees are as follows:

- Ceramics and inorganic
- Metals and magnetic
- Medical engineering and sensors
- Molecular electronics
- Polymers and composites
- Semiconductors
- Superconductivity

Some of these originated in the corresponding subcommittees within the old Engineering Board structure (e.g. Ceramics, Metals and Polymers), while others (Molecular electronics, Superconductivity, Semiconductors) started out as "Initiatives" originated within Science and Engineering Boards; more about Initiatives later. The Superconductivity subcommittee forms the SERC component of the joint SERC/DTI National Committee for Superconductivity (NCS), which was set up in response to the discover of high T_c superconductors. In fact it funds the whole of superconductivity research, theoretical, pure and applied, both high T_c and conventional. The role of the DTI (Department of Trade and Industry) within science funding will be discussed below. A similar situation obtains within semiconductor research: the MSEC subcommittee funds almost all activity in this area, which is dominated by research into superlattices and quantum wells (Low Dimensional Structures and Devices- LDSD). It follows that while the brief of Physics Subcommittee W is "Condensed Matter Physics", this does not include most of semiconductor research or all of superconductivity.

1.4 Other sources of funding (DTI, MoD)

The DTI directly funds only industrial programmes. Universities can be subcontracted by industry to carry out research under DTI programmes, but this is not at present a major source of research grant income. The LINK programme is a joint DTI/SERC scheme aimed at fostering collaboration between industry and universities, whereby individual programmes are funded 50% by Government (i.e. DTI and/or SERC) and 50% by industry. This has taken some time to get off the ground, but in the physics area there are now two programmes funded through MSEC, one in advanced semiconductor materials, the other in techniques of analytical and physical measurement (SERC to contribute about £5m p.a. in each area).

The Ministry of Defence (MoD) has a joint scheme with SERC, started in 1985, whereby it partly funds (up to 50%) research activity in the normal SERC grant rounds which is deemed to be of interest to the MoD's own research programmes. In practice, within the physics area, this produces extra funding for semiconductors, lasers and optics and superconductivity. The MoD's own laboratories, principally the Royal Signals and Radar Establishment, RSRE at Malvern, do fundamental research in these areas.

2. Distribution of funds

2.1 Breakdown of expenditure

The total funds for Science Board in 1990/91 amount to roughly £110m. As shown in fig. 2 roughly one third of this is allocated to research grants and another third covers the cost of central facilities. Postgraduate studentships account for about one quarter of the total. The remaining 8% is allocated to IRC's (Interdisciplinary Research Centres - more about these later). The breakdown of expenditure for SERC as a whole is very similar (see fig. 3).

In the face of the continued pressure for research grants (see next section), it has been SERC policy for some time to protect, and wherever possible, to enhance the grant line. The grant line has in fact grown by 8% over the four year period 1984-88, at the expense of expenditure on central facilities (fig.3). This process is continuing, and has led, in the harsh financial climate of the last year, to the closure of the Nuclear Structure Facility at Daresbury (the only domestic central facility of the Nuclear Physics Board). SERC has also recently been announced that the UK contribution to the Institut Laue Langevin (ILL) in Grenoble, France will be reduced by 50% from 1994. The ILL is a high flux beam reactor, funded jointly with France and Germany as equal partners until now. It is used for a wide range of condensed matter, material science and fundamental physics studies, and is the best neutron scattering facility in the world. It is not yet clear whether or how the ILL would survive this withdrawal of funding. The other central facilities funded from Science Board are ISIS, the pulsed neutron source based at the Rutherford Appleton Laboratory (RAL), the SRS (Synchrotron Radiation Source) sited at the Daresbury Laboratory, the ESRF (European Synchrotron Radiation Facility) at Grenoble (UK contributes ~15% of total budget) and the Central Laser Facility (CLF) at RAL.

2.2 Research Grants

The pressure on the grants line can be seen in fig.4, where the total demand is seen to have doubled over the ten year period 1979-89. The "alpha demand" corresponds to the proportion of the total judged by the peer review process to be of "alpha quality", and therefore deserving of support. In practice the money available has allowed only ~50% of alpha demand to be funded in recent years, and that at about 70% of the level requested. The last year 1990/91 was an exceptionally bad one, due to a difference between SERC's expectations and its actual share of the science vote: the grant line dipped to about half the 1989/90 figure.

The distribution of research grants among higher education institutes (HEIs: i.e. universities and polytechnics) is highly non uniform. Out of a total of 90 HEIs, the top ten universities take 50% of the total of Science Board grants (by value, 1987 figures), while the top 20 universities take 70% of the total.

2.3 Initiatives and IRCs

Initiatives are coordinated research programmes designed to encourage and direct research into fields of particular scientific importance. Physics Committee has been particularly inventive at stimulating initiatives. One of the first was the LDS (Low Dimensional Structures) initiative in the semiconductor area. This funded five growth centres, based on MBE or MOCVD methods, at different universities, plus associated research groups to study the physics of semiconductor quantum well structures and superlattices. Probably none of this work could have been funded under the conventional "responsive" mode for research grants. Such programmes have their own coordinators, and specialist panels with industrial representatives. LDS did much to revitalise semiconductor research in the UK. It has developed to incorporate more applied aspects into the programme (LDSD) and has now evolved from an initiative into a subcommittee under MSEC. Other notable initiatives in the physics area are Non Linear Optics (NLO) and Magnetism and Magnetic Materials (MMMI). NLO is still funded largely through Physics Committee. MMMI, which covers both pure and applied aspects of magnetism, is jointly funded between Physics Committee and the Metals and Magnetism Subcommittee of MSEC. As in the LDS case the magnetism initiative has provided funding for several large equipment items, including two MBE growth facilities for magnetic metal superlattice production, which could not have been funded in the normal grant round. The burgeoning of initiatives has been criticised in some quarters of the academic community as taking funding away from the "responsive" grant line. Within Science Board it is argued that without exciting new programmes it would be impossible to maintain its share of the cake.

Interdisciplinary Research Centres (IRCs), the first of which were funded in 1988, are intended to provide centres of excellence allowing British scientists to compete at international levels in research programmes requiring a highly interdisciplinary approach. They are expected to have a limited life of up to 10 years. In the physics area the first two tranches included the IRCs in Superconductivity (Cambridge), Surface Science (Liverpool), Semiconductors (Imperial College, London) and Optoelectronics (Southampton). These involved the setting up of a rolling programme, initially for six years, at a cost of ~£6m each. It is not clear whether any further IRCs will be forthcoming.

3. References

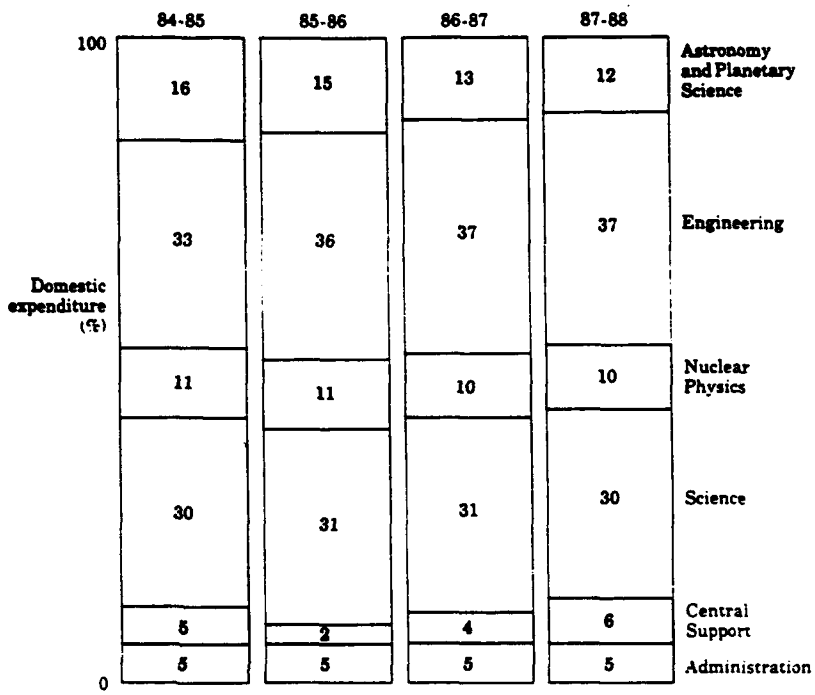
SERC Physics Committee Report 1985-88

Report of the Science and Engineering Research Council 1987-8

SERC Corporate Plan 1989

"A Strategy for the Support of Core Science", SERC, 1990

Fig. 1 Domestic expenditure by SERC Board



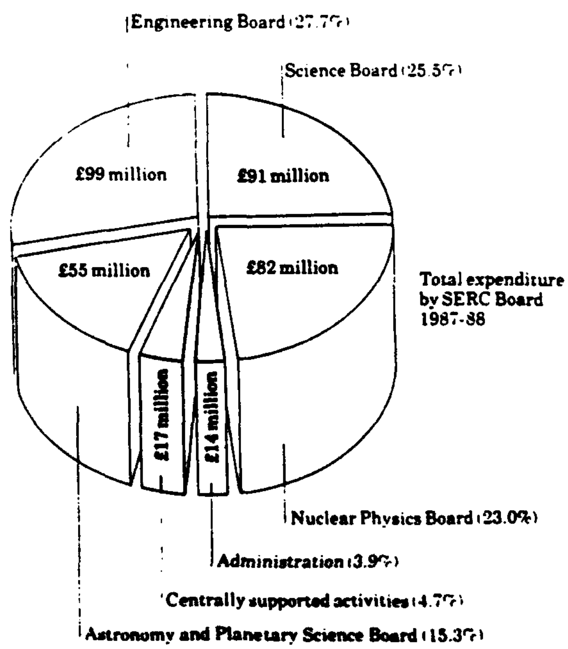
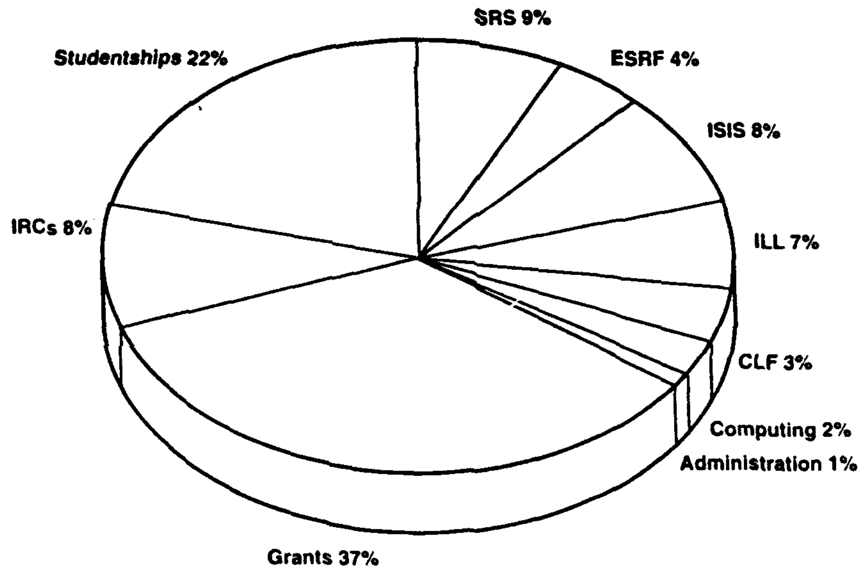


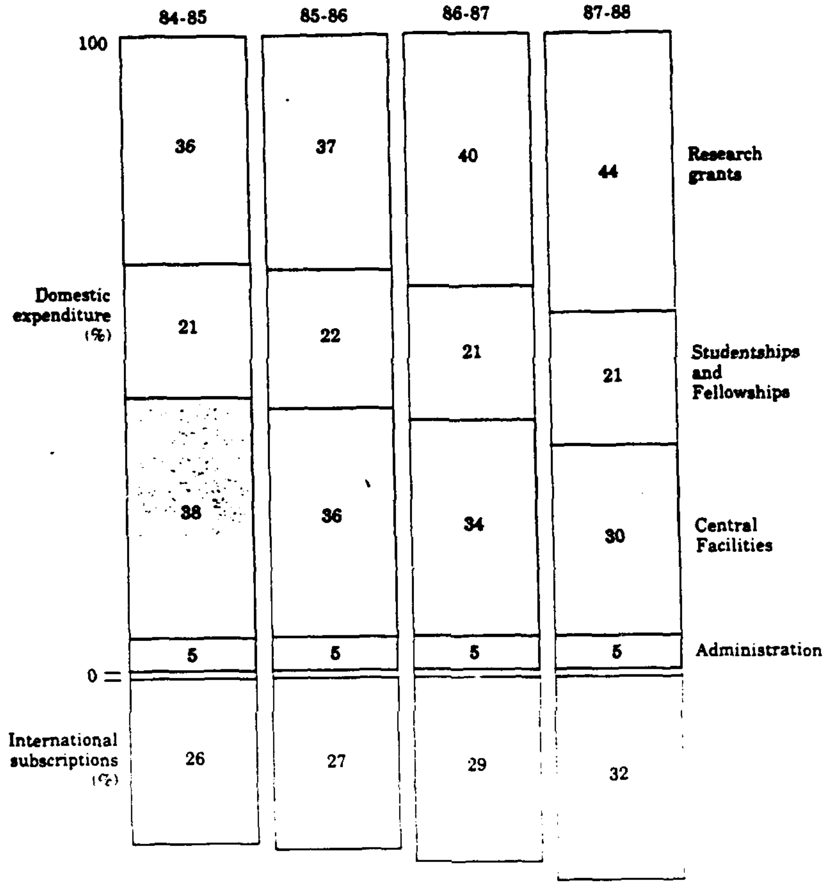
Figure 2:: Distribution of Science Board Funds, 1990/91



Key:

SRS	Synchrotron Radiation Source
ESRF	European Synchrotron Radiation Facility
ISIS	Spallation Neutron Source at RAL
ILL	Institut Laue-Langevin neutron source
CLF	Central Laser Facility
IRCs	Interdisciplinary Research Centres

Fig.3. **Expenditure by SERC activity (% of domestic)**



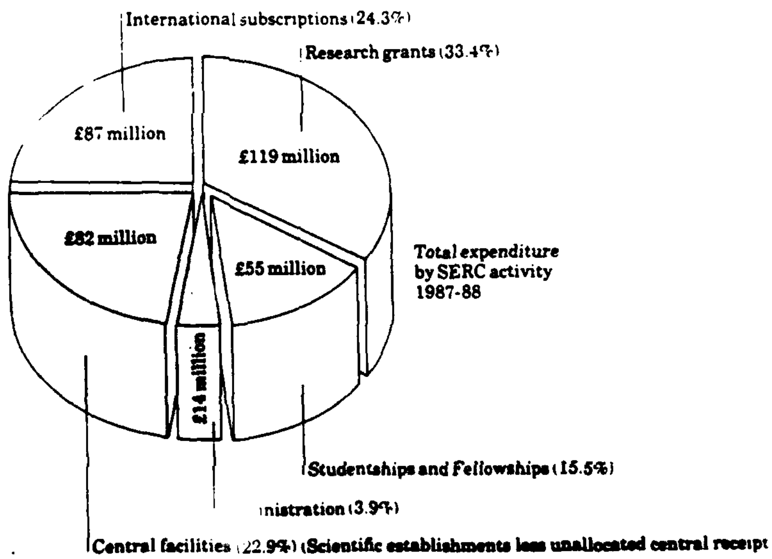
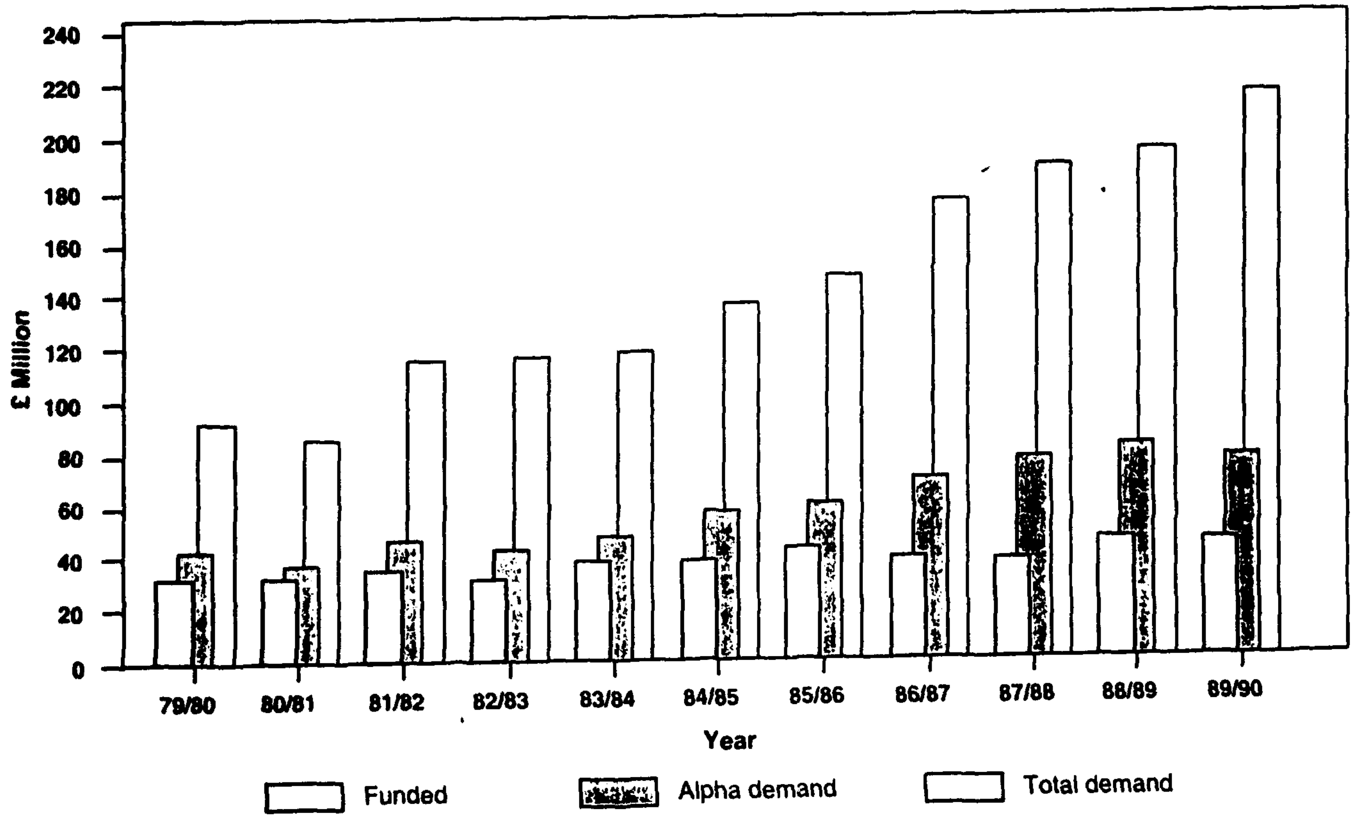


Figure 4 : Science Board Grant Statistics by Value (at constant 1989/90 prices)



Note: Excludes data on Biotechnology, IRCs and LINK
Includes an estimate for Science Board provision for Materials Commission

Appendix II:

A PERSPECTIVE ON THE BUDGET OF THE U. S. ARMY RESEARCH OFFICE: CONDENSED MATTER PHYSICS PROGRAM

Mikael Ciftan, US Army Research Office N.C.

Before getting into the budget of the U. S. Army Research Office (which includes the budget of the European Research Office (ERO) located in London, UK), it would be appropriate to refer readers to the article published in American Institute of Physics journal *Physics Today*, June 1990, pages S1-S8, in order to gain an appreciation of where the Army Research Office (ARO) stands in relation to the rest of US funding of R&D.

Note that Army's overall basic research funding is approximately $170-180M and gets broken down further as discussed in a second informal document that our Physics Division has authored (reproduced here as Annex to Appendix II). There you can see the way the Army Research Office portion is selected in relation to the other parts of the Army's research community. It is however to be noted that much of the "basic research" in the Army Laboratories and elsewhere in these sections may be more accurately categorized as "basic-to-applied" type research, perhaps trying to bridge the gap between basic and applied. In a real sense, this type of bridging is definitely needed, especially in those areas where we have been able to identify Army-relevant applications that we have had to champion and define those gaps in knowledge in the basic sciences that had to be filled. The in-house laboratory Independent research category again falls into this exploratory type of activity to identify critical areas to be explored.

Next you will note that a large portion of the $70-$80M allotted to ARO is further decimated by programs that *a priori* take away substantial portions of the budget thus leaving a much smaller "core" budget, the part that we have direct control as to how we spend. By this latter remark I mean the freedom of choosing projects that have a particular "single" investigator or small group of investigators in subareas in each of the scientific disciplines. Note again that ARO scientific divisions are established according to the classic method of subdividing the hard sciences into Physics, Chemistry, Biology, Mathematics, Engineering and Electrical Engineering, Materials Science, Geosciences.

Of course, just because a division is an engineering division does not imply categorically that the work supported by such a division is more applied than that in, say, physics. There are many fundamental basic engineering problems at a phenomenological level of detailed

understanding. Here at ARO we have the unique opportunity and capability to select truly innovative projects at the very basic level;however, we also feel that we need to forge technology transfer towards the applied and find those barrier basic research issues that need to be tackled if a transfer is to be realized as hoped for. Therefore the projects that we support tend to cover a wide spectrum of "basicity". In fact we have numerous examples of research that we singlehandedly supported and was published in journals such as The Physical Review and Physical Review Letters (say in the Physics subarea) which found their way into applied journals and finally into commercial products and other applications!-- and we had not left these transfers to happen by chance but had forged them. Truly scientific breakthrough cannot be "planned" but can be nurtured. We typically get excited in an abstract, sometimes way-out idea, and try to see if it opens up new avenues of thinking, new mathematics, new concepts, new devices, etc.

Next we look at the way the ARO budget gets sliced into the portions allotted to its scientific divisions. We see that the Physics budget has also declined from its FY90 value to the present FY91 vale of $4.7M. We note that the core program of ARO has declined to $38.6M. The "set aside" assessments to ARO amount to some $1 9.3M, a very substantial portion of the budget. You note that ERO gets $1 M, and although we do have some control over it, ERO has more direct control over its decisions, the precise mechanisms and procedures for the selection of proposals. I believe, however that there will be some restructuring in the future at ERO--again, in my personal view, in order to better reflect the unusual opportunities that can be cultivated in a cooperative mode together with ARO. By more thoroughly integrating with the ARO activities a better synergism can be achieved-- again my personal view.

While we are discussing ERO, it is important to get an appreciation of the way its scientific Divisions have been structured. There have been four divisions; Mathematics-Physics, Chemistry-Biology, Electronics-Computer Science, and Mechanical-Aeronautical Engineering. The $1 M divided into these divisions does not appear to provide sufficient funds to support "programs" in the subareas of each of the sciences. Even so, by very careful injection of the available funds into specific projects substantial contributions to the sciences have been produced. A very good example of this is the partial support of the work of Professor Michael Pepper with which I specifically want to illustrate this synergetic role of ERO. Professor Pepper had received a very small amount of funds from ERO with which he was free to construct a special device at an industrial laboratory when he was unable to do the same with University funds because of normal constraints on the latter. He then brought the device to von Klitzing to make certain measurements on and they discovered the Quantized Hall Effect that led to the Nobel Prize on this new effect; the very first

announcement of the quantized Hall Effect was published by him, von Klitzing and Dorda in *Physical Review Letters* 45, 494, 1980. He has stated, in writing, that it was the freedom that ERO funds provided that helped him achieve this result. The history of ERO supported work is replete with such synergisms. There are numerous instances where ERO has provided substantial help to scholars from prominent institutions of learning in the US to go to those in Europe and vice versa to pursue specific scholarly work.We can now turn to ARO. It is important to note that the various Divisions within ARO work very closely together, in many instances supporting projects jointly as the case may necessitate due to its cross-disciplinary nature. Proposals for projects are routinely and informally circulated through various Divisions in an effort to find the best home(s) for them. A lot of times these proposals are also communicated with other agency project monitors, again to find the best combination of homes and possibly for joint funding. Also there are very frequent formal and informal modes of reviewing the programs of ARO Divisions and/with those of outside agencies which help amalgamate the selection of the projects and the ultimate decisions on funding.

Next we focus down onto Physics itself within and outside of the ARO. It is instructive to compare the areas of physics supported by the ARO and its equivalents in the Navy and the Air Force. We find that the ARO has a strong commitment in Condensed Matter Physics but relatively little in Plasma Physics. However the Air Force and the Navy are definitely more interested in Plasma Physics for obvious reasons. Yet we do support very select unusual projects in plasmas, such as ones in conjunction with condensed matter and the fundamental interactions in the growth of materials. A very specific example would be plasmon polaritons in solid state materials on which we have supported work in the past.

Now we can focus on the Physics Division of ARO. Although the Atomic - Molecular part of the physics program appears small, significant innovative work is being supported. An example is "Atom Interferometry" where one tries to use the de Broglie waves of atoms in interference mode to attain a new level of extremely large resolution and pattern making at exceedingly small dimensions, while at the same time probing fundamental physics issues. In the past we have been instrumental in developing the interface between physics and chemistry by, for example, supporting work that used many-body theoretical techniques of nuclear physics applied to the chemistry of molecules very successfully; specifically, work on the coupled-cluster method was supported that was so successful as to predict the correct experimental heats of reactions that had thereafter forced the experimentalists to redo their experiments and concur with the calculated predicted results. Another topic that falls between Atomic/ Molecular and condensed matter/solid state is the physics and chemistry of atomic clusters that we

have championed now for a number of years. Laser spectroscopic techniques, atom trapping, details of rotational-vibrational-translational energy etc. exchange mechanisms, collisional, excitational and relaxational spectroscopies also fall into this category. Quantum Optics may fall into this area and/or condensed matter physics depending on the main thrust(s) of the work. Therefore this Atomic/Molecular category may actually be much larger than it appears from the pie chart.

Classical Phenomenology encompasses Classical Optics and the interaction of electromagnetic fields with matter at the macroscopic phenomenological level. Examples would be the generation of femtosecond high power tunable mid-infrared pulses using the free-electron laser mechanisms, tunable synthetic non-linear materials, nonlinear guided waves, structure and switching dynamics in ferroelectric crystal and liquid crystal thin films, synchrotron X-ray diffraction studies of the photorefractive effect, novel concepts in scanning-tunneling microscopy.

We finally focus onto the Condensed Matter Physics Program itself, the topic of our "Round-Table Workshop". By now it is clear that there are no rigid boundaries in our program in physics and that is because of the innovative nature of the research works that we support which often break artificial barriers anyway. Therefore the Condensed Matter Physics portion of the program is infused with work from other subareas as well as getting itself infused into these other areas. Nevertheless, if we take these boundary crossing into account, on balance this subprogram has an approximate budget of $1.5M at ARO. Considerable cross-coupling exists with projects in the Electronics Division, Geosciences Division, at times the Mathematics Division, Materials and Chemistry Divisions as well.

However the Physics Division part of Condensed Matter Physics tries to concentrate on the very basic physics issues, particularly emphasizing microscopic mechanisms whenever appropriate. One way of cross-sectioning of the program reveals that we have, in FY 1990, covered the following topical areas: localization, frustration, disorder; size and dimensional effects/restricted dimensionality effects, atomic clusters; elementary excitations, plasmons, phonons, magnons, etc.; quantum wells, heterostructures, nanoscience, as special restricted dimensionality area, with electronic transport as well as optical etc. excitations; surface and interfacial effects, and the associates elastic, magnetic, optical etc. effects in particular. quantum optics of the solid state, and quantum optics in general; radiation physics; millimeter / submillimeter wave optics, display physics, ferroelectrics.

Another "cross-sectioning" of our program that I have done would reveal a great number of technology transfers that have sprung from these

projects of very basic research. Most of them did not happen by serendipity but were due to a proactive mode of forming our program and extensive collaborative efforts that were simultaneously and consciously forged.

It is noteworthy that in the past we have made substantial contributions to low temperature physics and specifically superconductivity, particularly our support of the work that was written up in the very first BCS theory paper that resulted in the celebrated Nobel Prize in Physics; also we have made contributions to high pressure physics, the alloy problem the successful calculation of phase diagrams from first principles, to cite a few.

The reason to bring this last point up is that with the limited budget we have tried to "walk through" the various subareas of physics as innovative ideas spring up and allow us to do so, in order that over a period of a few years- and certainly over a decade- we are sure to cover most of the subareas of Condensed Matter Physics in our program at ARO.

Annex to Appendix II:

December 4, 1990

Physics Division

SUBJECT: The Army Research Budget

Dear :

The Physics Division staff wanted to share with you information about the past and current research budget. This information may explain some of the problems with funding resources that you have encountered this year. It may also affect your contingency planning for future years.

The Army's research budget is divided into a number of components. In FY90, the distribution was:

1) Medical research (The Surgeon General) – $36.9M
2) Research for the Corps of Engineers – $7M
3) Research in the Social Sciences (The Army Research Institute) – $3.7M
4) Research in the Army Laboratories – $64.8M
5) In-house Laboratory Independent Research (All Army Laboratories) – $9.1M
6) Extramural Research (The Army Research Office) – $79.3M

The only budget of interest to most of you is the Army Research Office budget. That budget has remained approximately the same size throughout the 1980's. In Figure 1, we show the ARO budget from FY84 to the present. Most of the programs labeled Single Investigator and Special Programs are associated with those research projects selected in the traditional mode of operation of the office. An investigator submits a research idea and a plan of execution; the proposal is peer reviewed; and the "best" proposals are funded. Most of you obtain your funding through this mechanism.

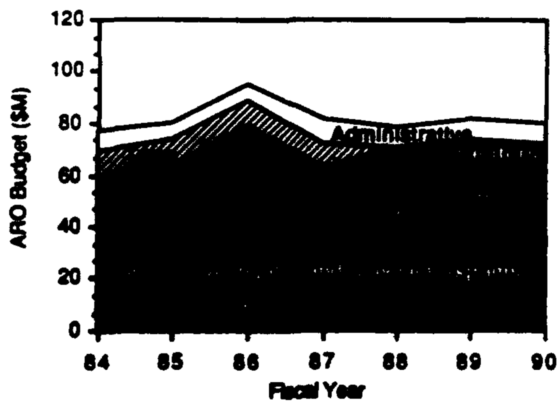


Figure 1. ARO budget for fiscal years 1984 through 1990. The data in figures 1 and 2 are not corrected for inflation. The URIP is the University Research Instrumentation Program; URI the University Research Initiative; Centers the JSEP, JSOP, Math Center, Rotor Craft Center, and AI Centers; and the administrative includes all ARO salaries, benefits, travel, office costs, etc.

Approximately 9% of the budget is used for ARO's operating cost. This expense, which has been at this percentage for 20 years, is labeled Administration. The URIP is the research equipment program initiated by Congress and administered by this office in the early 80's. The office supports a number of centers in areas of technology we wish to emphasize such as optics, mathematics, and rotorwing aerodynamics. You will notice that there was a large increase in ARO's FY86 funding that was associated with the University Research Initiative created by Congress in that year. In FY87, and the years following, the funding of the URI program was obtained from the normal research program funds. In an attempt to smooth the funding perturbation resulting from the initiation of the URI, we split-funded a number of research contracts. A split funded program receives less than twelve month funding in its initial year. This procedure saves money the first year but increased the obligations in later years. Split funding resulted in an increase of ~15% in our FY90 budget.

The Single Investigator program decreased at the expense of the URI program beginning in FY87. However, more recently, a number of other special programs have been initiated outside of the traditional research community that also have resulted in a decrease in the core funds. Figure 2 shows the distribution of funds labeled Single Investigator and Special Programs in Figure 1. As can be seen, the money available for the core program has decreased by 15% from FY89 to FY90.

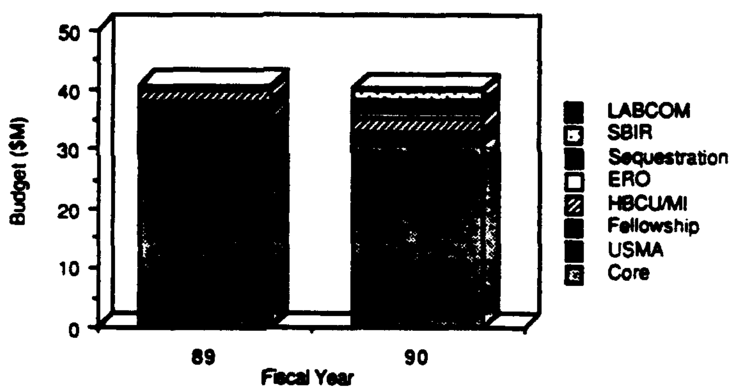


Figure 2. Single investigator and special program funding for fiscal years 1989 and 1990. The key is the following: Core - single investigator; Fellowship - NDSEG Fellowship Program; HBCU/MI - Historically Black Colleges and Universities and Minority Institutions; ERO - European and Far Eastern Research Offices; Sequestration - Gram Rudmann; SBIR - Small Business and Innovative Research; LABCOM - a required contribution toward the operation of ARO's parent organization.

The Physics Division shares equally with the other disciplines in the decrease in funds available for our core program. This year, FY90, we expected a budget equal to last year's, after inflation. That would have given us a budget of $6.0M for the core program. Because of an increase in demands for special programs such as Small Business Innovative Research, Army Fellowships, etc., we found that the core program budget contained only $5.0M. Our contracts and grants normally are for a period of three years, so the budget decrease and the obligations incurred from split funding prevented the initiation of any new contracts without radical adjustments. As most of you are acutely aware, we reduced virtually all contracts for FY90 and FY91 by 16-20%. Exceptions were made for contracts which had received their FY90 allocation before we were informed of the budget cut. Even with these draconian cuts,

fewer than 50% of the normal number of new starts will be possible in FY90.

We want to support the maximum number of high quality research projects allowed by our budget constraints and the limits dictated by the levels needed for a viable project. We conduct our own research and thus are well aware of the problems these reductions create for you. We hope that you can find additional support from other sources. We must warn you that from our point of view the expected Peace Dividend is a phantom. As you can see from Figure 3, the entire DoD budget will not meet the unmet needs of the current Federal Budget. The contract research business should be a buyers market in the near future.

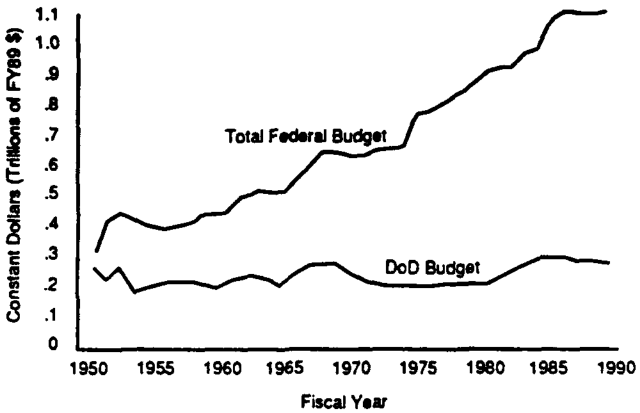


Figure 3. Comparison of total Federal and Defense spending.

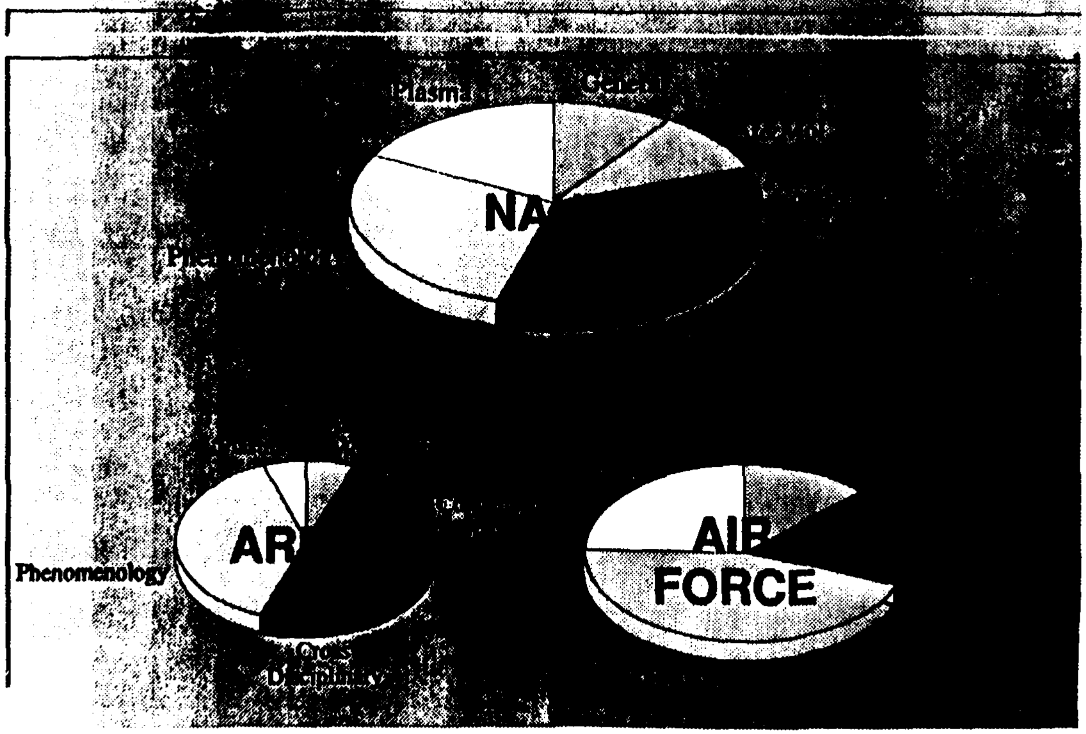
We appreciate your efforts for the Army research program. We expect a more competitive but more stable funding climate beginning in FY91 and hope that we can find the least disruptive procedures for overcoming the current funding problems.

Sincerely yours,

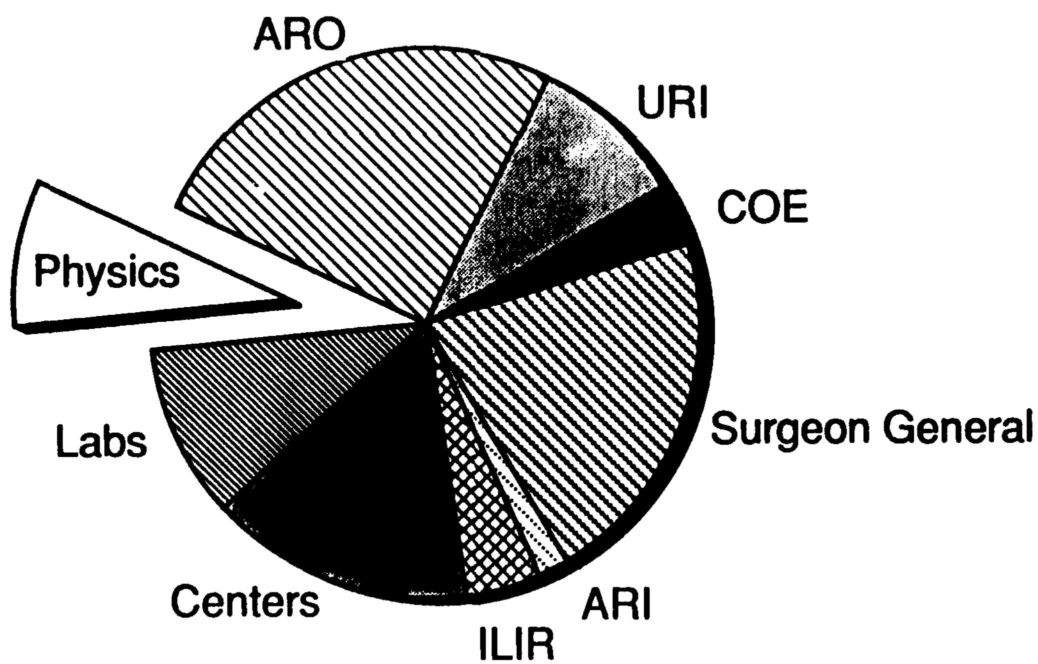
David Skatrud Bob D. Guenther Mikael Ciftan

PLANNING BUDGETS FY 91		FY90 ($K)	FY91 ($K)
BIOSCI		2,302	2,103
CHEM		4,935	4,509
ELEC		10,388	7,664
ENG		5,680	5,190
GEO		2,810	2,568
PHYS		5,182	4,735
MATLS		5,163	4,718
MATH		5,813	7,139
TOTALS		42,273	38,626

FY 90 Physics Research



FY90 Army 6.1 Budget



Army Research